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POLAR-AURORAL CHARGING OF THE SPACE SHUTTLE AND EVA ASTRONAUT

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SUMMARY

Spacecraft charging in low-altitude polar orbit has recently become recognized as a significant environmental interaction. The same conditions needed for spacecraft charging at geosynchronous orbit are also found at times in the low-altitude polar-auroral environment. The required conditions are high fluxes of energetic electrons, low plasma densities, and darkness. The energetic electrons are found in very bright active auroras. Plasma densities are occasionally low enough in polar regions but, more importantly, a large body such as the Shuttle sweeps out the ambient ionospheric plasma to produce a cavity in its wake. The POLAR charging code has been used with measured parameters for energetic auroral electrons and plasma densities to evaluate polar orbit charging. The Shuttle can be expected to charge at times to thousands of volts while the astronaut during ~~extravehicular activity~~ (EVA) can charge to hundreds of volts. The multibody charging problem of the astronaut in the wake of the Shuttle, a more complicated problem, is being evaluated. Laboratory test results ~~will be~~ presented that confirm charging and subsequent arc discharge of EVA equipment material samples. Induced current and radiated radio frequency electromagnetic interference (EMI) were measured from the arc discharges. Such EMI could cause potentially dangerous EVA equipment anomalies. Ground tests of subsystems and the complete EVA equipment system are needed. Orbital tests to validate model predictions and understanding of polar orbit Shuttle wake charging will be proposed.

INTRODUCTION

The advent of manned polar orbit flights from Vandenberg AFB increases the importance of environmental considerations which have not been significant to previous Shuttle missions. Passage over intense auroras may result in polar-auroral charging and subsequent arc discharge. Recent measurements on Air Force polar-orbiting meteorological satellites confirm that charging does occur and provide values for the environmental parameters contributing to the charging (1). The concern is primarily for arc-discharge effects on the existing extravehicular activity (EVA) equipment and, through the equipment, for the astronauts. The auroral radiation responsible for surface charging is too low in energy to be a direct radiation hazard to the astronauts or their equipment. The Shuttle is not considered to be at risk from arc-discharge because it was designed to withstand direct lightning strikes and has extensive redundancy; e.g., five computers. It has previously passed through the fringes of the high geomagnetic latitude areas during 50 and 57 degree inclination flights from the Kennedy Space Center with no reported problems.

An additional factor that has not been fully evaluated is that the Shuttle and the astronaut on EVA, who can be considered an independent spacecraft, make up a system of electrically isolated spacecraft. They have a wide disparity in size and are immersed in the ionospheric plasma. Our previous experience in both geosynchronous and polar orbits has been with individual isolated spacecraft.

Spacecraft charging is the result of the combination of several factors; a strong source of energetic electrons and insufficient neutralizing plasma. Darkness is also a contributing factor, particularly in low polar orbits, since photoelectrons resulting from solar ultraviolet irradiation counteract charging. Auroral electrons producing intense auroras can provide an adequate supply of electrons with the requisite energy. Experimental measurements in the Shuttle payload bay on STS-3 and STS-4 have shown large plasma density reductions in the payload bay in the wake orientation compared to the ambient plasma (2, 3). The most intense auroras normally occur at local midnight hours which invariably are in darkness.

The threat to astronauts due to susceptibility of the existing EVA equipment to electromagnetic interference (EMI) is difficult to assess. We are concerned because a strong link has previously been made between satellite charging and subsequent arc discharge (4) and operational upsets and failures, even the loss of a satellite (5), at geosynchronous altitudes. Charging can also cause deterioration of spacecraft materials and can enhance contamination due to the deposition of undesirable materials on critical surfaces (6).

Equipment problems that might be direct hazards to the astronauts are not the only reason for investigating the susceptibility of the EVA equipment to charging and arc-discharge. Equipment failures to sub-systems such as the communications link would not be a danger to the astronaut but might cause cancellation of planned operations. An example is the recovery of the Teal Ruby spacecraft that has been announced as being under consideration. Rescheduling of such an operation would not only cost millions of dollars but could result in years of delay due to the present Shuttle schedule pressure.

The measurements by the Air Force Geophysics Laboratory (AFGL) Space Particles Environment Branch of the charging of the Air Force Defense Meteorological Satellite Program (DMSP) spacecraft and the environmental conditions which contribute to it will be reviewed. Spacecraft charging computer code results will be compared with the charging levels measured. These codes will then be used to predict the potentials to which the Shuttle and the EVA astronaut will charge if severe charging conditions are encountered. New laboratory results will be presented that show the fabric materials in space suits will charge and produce arc discharges when subjected to electrons with the same energies as measured in auroras. Tests are planned to investigate charging of EVA equipment in a simulation chamber and the susceptibility of EVA equipment to arc-discharges.

POLAR-AURORAL SATELLITE CHARGING

Charging of polar-orbiting Air Force DMSP satellites has recently been documented (1). Few examples of spacecraft in the ionosphere charging beyond a few volts have previously appeared in the literature partly because of the limitations of instruments used to detect particles and plasmas. This impasse has been overcome with the launch of the DMSP satellites designated F6 and F7. Each satellite carries the AFGL SSJ/4 electron and ion analyzer instrument, which measures precipitating electrons and ions, and SSIE thermal plasma detector instrument. A generous geometric factor for the ion detector allows the application of a technique regularly used to identify the degree of charging for satellites at geostationary orbit. A large count rate should be seen in an energy channel centered near the spacecraft potential because of the acceleration of cold ionospheric ions by the spacecraft charged to a negative potential.

A preliminary search of early DMSP/F6 satellite measurements shows that such charging events frequently appear at the time that intense inverted-V auroral electron structures are measured, as shown in Figure 1 (7). The upper portion shows the measurements from two channels of the particle spectrometer showing the greater than 5 keV and greater than 10 keV auroral electrons. The satellite was traveling from the center of the polar cap to lower latitudes and passed over a strong auroral display. Below is shown the value to which the frame of the spacecraft charged, reaching a maximum of -462 V in the second peak. It can be seen that the spacecraft charging closely follows the peaks of energetic auroral electron fluxes. The fact that the spacecraft was charged at this time was verified using the SSIE thermal plasma probe on the same vehicle. The SSIE data emphasized the important contribution of decreased plasma density in order for the DMSP to charge to values of hundreds of volts. Modeling studies using the POLAR code indicate that dielectric surfaces on the wake side of the vehicle could charge to many times this value. These results clearly establish the existence of polar-auroral spacecraft charging.

COMPUTER CODE MODELING OF POLAR-AURORAL CHARGING

Comparison of measured and calculated charging

Spacecraft charging computer code models developed by the Air Force and NASA have been used to analyze the charging conditions which the DMSP encountered (8). The derivation of the methods used have been described elsewhere and will only be summarized here (9). The charging codes predict that the DMSP would charge to -547 V, in close agreement to the -462 V measured. The calculation used the ambient plasma parameters and the auroral charging currents measured on DMSP at the time the charging occurred.

Charging of an Individual Spacecraft

The charging codes show that charging increases as spacecraft size increases. The Shuttle can be expected to charge even more than DMSP. A previous study (8) compared spheres covered with teflon, a typical spacecraft surface material. A Shuttle-sized object will charge to -3545 V and an astronaut-sized object to -172 V for an ambient ion density of 125 ions/cubic cm and a weaker aurora than that which charged DMSP to -462 V. Secondary and backscattered electrons resulting from incident energetic electrons are one of the fundamental factors controlling spacecraft charging. A change in the surface material, with resultant change in secondary and backscattered electron yields, will change the potential to which a spacecraft will charge. More recent results (9) used the actual characteristics measured for the Shuttle thermal tile materials (10).

Charging Calculation Parameters

The values of the energetic auroral and plasma values measured by DMSP/F7 at 49,843s UT on 26 Nov 83 will be used for the charging calculations in the rest of this section. The ambient ion plasma density was 125 ions/cubic cm and the energetic auroral electrons were modeled by a Maxwellian distribution with 10.1 keV characteristic energy and characteristic density of 3.9 electrons/cubic cm (1). POLAR charging code calculation results show that the Shuttle would charge to -3290 Volts using these parameters.

Charging of Multiple Spacecraft

The charging codes were used to calculate the charging of the multiple spacecraft system consisting of the Shuttle and the astronaut conducting nearby EVA in the wake of the Shuttle (9). Figures 2 and 3 show the models of the EVA astronaut and Shuttle used in the POLAR charging code calculations. Figure 4 shows the combined, multiple grid model. The contrast in size is clear. Figure 5 shows the space potentials for the combined system. It can be seen that the potential contours show little effect of the presence of the EVA astronaut at distances equal to several times his size.

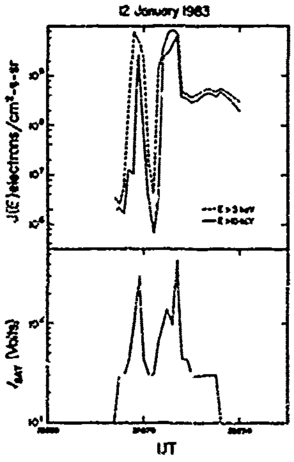


Figure 1. Top: Auroral Electron Fluxes greater than 5 and 10 keV. Bottom: Potential of DMSP.

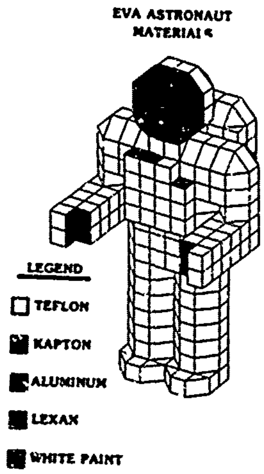


Figure 2. EVA astronaut model used in charging code calculations.

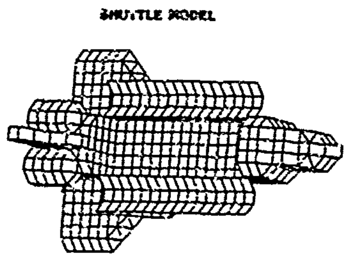


Figure 3. Shuttle model used in charging code calculations.

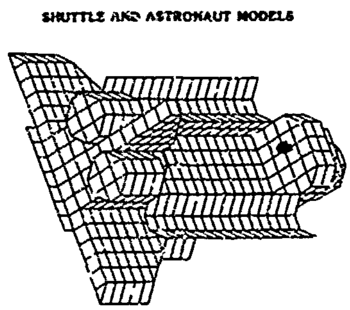


Figure 4. Combined multiple grid model of Shuttle and EVA astronaut.

Difference Charging of Shuttle and EVA Astronaut

The term "difference charging" will be used in discussing the difference in potential between nearby spacecraft. This is to avoid confusion with differential charging which traditionally has been used to describe the situation where different surface elements on the same spacecraft are at different potentials.

The calculation of the difference charging of the Shuttle and EVA astronaut took advantage of their large disparity of size. For this case it was shown that the distance from the smaller spacecraft at which the space potential is dominated by the larger spacecraft is related to the square root of the product of their sizes. This distance is approximately 3 meters for the EVA astronaut and the Shuttle (see Figure 5).

The space potential at a location close to the Shuttle, compared to the location of the sheath edge where the ambient thermal ions are first affected by the Shuttle, will be approximately equal to the Shuttle potential of −3290 V. The ambient ions involved

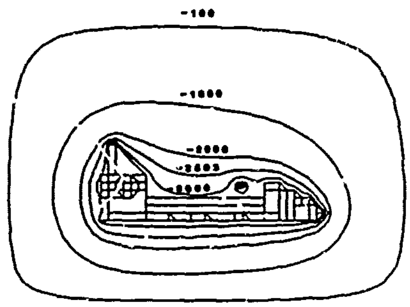


Figure 5. Potential contours of Shuttle and EVA astronaut from POLAR code calculation.

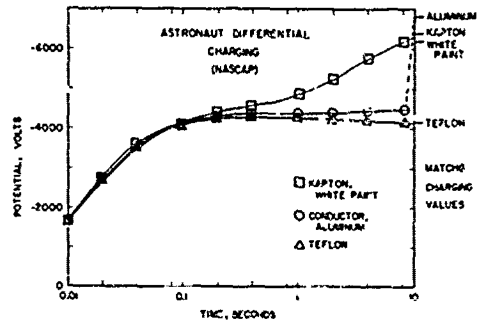


Figure 6. Time history of charging of astronaut model surface elements from NASCAP code calculation.

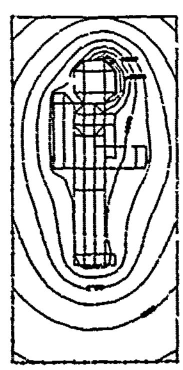
with the balancing of the energetic auroral electron current to the Shuttle will have acquired an energy due to this when they first feel the effects due to the presence of the second spacecraft, the EVA astronaut, who is also attracting ions to balance the energetic auroral electron current.

The smaller spacecraft can be considered to be immersed in an energetic ion beam, rather than moving with orbital velocity in an ambient thermal ion plasma. The ion collection situation for the EVA astronaut is similar to a probe in a monoenergetic ion beam, where the beam energy is due to the potential of the larger spacecraft. The scale of Figure 5 does not clearly show that the Orthofabric (outer surface consisting primarily of Teflon) which covers most of the Extravehicular Mobility Unit (EMU) is charged to approximately -4140 V, much greater than the -172 V which the astronaut charged to under similar conditions when not near any other object. The difference in potential between the Shuttle and the astronaut is 850 V.

Differential Charging of the EVA Astronaut

The NASCAP charging computer code was used to calculate the charging of the detailed model of the EVA astronaut shown in Figure 2. The time history of the charging of the surface elements identified is shown in Figure 6. It can be seen that several of the elements charge up to within 10% of the final value within 0.1 seconds. Other elements charge more slowly and still have not reached their equilibrium value at 8.3 seconds, the time at which this calculation run terminated. The differential charging between surface elements of different materials develops more slowly than the absolute charging. The Kapton and Teflon surface elements of the glove have the largest differential charging for the elements shown in this run. At the end of the run, the Teflon potential is only 67% of the Kapton potential. The differential charging was within 10% of this in 3 seconds (Teflon at 77% of Kapton). These locations are significant since they are adjacent surface elements of the astronaut's gloved hand which would be used to grasp objects. The details of the potential contours around the EVA astronaut are shown from the side in Figure 7 and from the front in Figure 8.

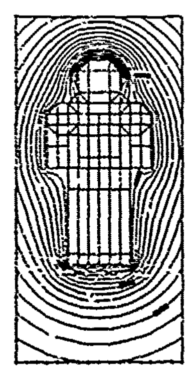
EVA ASTRONAUT
POTENTIAL CONTOURS



SIDE VIEW

Figure 7. Side view of potential contours around EVA astronaut from NASCAP code calculation.

EVA ASTRONAUT
POTENTIAL CONTOURS



FRONT VIEW

Figure 8. Front view of potential contours around EVA astronaut from NASCAP code calculation.

Application to Operational Planning

The recent results of the POLAR and NASCAP computer code modeling of the Shuttle and EVA astronaut are applicable to polar-orbit EVA in several ways:

a. There is little difference in charging of the EVA astronaut between a ram position or a wake position if he is close to the Shuttle. A distance of 2 meters was considered a conservative value. Conservative means that the statement is unequivocal for distances of 2 meters or less and probably holds for greater distances, dying away as the distance approaches the sheath boundary at 10-20 meters.

b. Computer runs illustrate the short time periods needed for development of absolute (EMU frame potential relative to space potential) and differential (one place on the EMU relative to a different place) charging. For the conditions measured on DMSP, absolute charging is within 90% of ultimate within 0.1 seconds. Differential charging is within 90% of ultimate within several seconds.

c. Differential charging can be, conservatively, as much as 30% of the greatest value. For this same example, the spacesuit Orthofabric (Teflon) surface is at -4140 V and the Lexan face mask is at -6150 V, a difference of 2010 V.

LABORATORY TESTS OF SPACE SUIT MATERIAL

EMU fabric material provided through AFGL has been tested at Jet Propulsion Laboratory (JPL) and SRI International. The EMU fabric consists of an outer layer of Orthofabric, five layers of aluminized Mylar for insulation and a Neoprene coated Nylon rip-stop layer.

Space Suit Material Tests at Jet Propulsion Laboratory

Samples with areas of 10, 100 and 1000 sq. cm. were irradiated with a 15 keV monoenergetic electron beam with current density in the range of 1-5 na/sq. cm. in the experimental apparatus shown in Figure 9. Several modes of discharge were identified which can intermingle or occur simultaneously:

a. Glow is associated with stitching exposed to the charging source. Once started, the glow occurs continually. It acts, in a way, as a dissipative mechanism. The existence of glow discharge does not prevent the occurrence of the other discharge modes.

b. Blowoff discharge of the Orthofabric outer layer, as illustrated in Figure 10A, is a discharge to the residual plasma, equivalent to space conditions at orbital altitudes, in the vacuum chamber. The peak current measured is not significantly dependent on the areas of this group of samples. The typical rise time and pulse width were 17 ns and 25 ns. The peak current of 0.2 A measured with this apparatus was relatively low compared to values for homogeneous dielectric materials, such as Teflon and Mylar, where peak currents have been as large as 50 A.

c. Direct discharge of the aluminized Mylar (second) layer, under the Orthofabric outer layer, to the grounded metallic sample holder, as illustrated in Figure 10B. The woven structure of the fabric allows electrons to penetrate through the first layer to the second. In another test, a meter connected directly to the conducting aluminized layer showed a steady state current of 40% of the incident beam current. The arc-discharge current is proportional to the sample area to the 0.4-0.7 power. A peak pulse current of 0.5 A for the 100 sq. cm. sample and 2.2 A for the 1000 sq. cm. sample was measured in the conductor which grounds the metallic sample holder. The rise time for a typical direct discharge was 2-4 ns and the pulse width was 5-10 ns, noticeably less than for the blowoff discharge. Pulses with faster rise times are more likely to cause undesirable effects on electronic circuits.

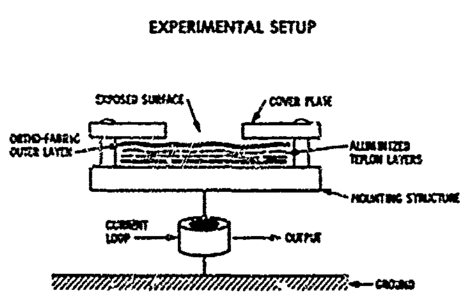


Figure 9. Experimental apparatus for spacesuit material tests at JPL.

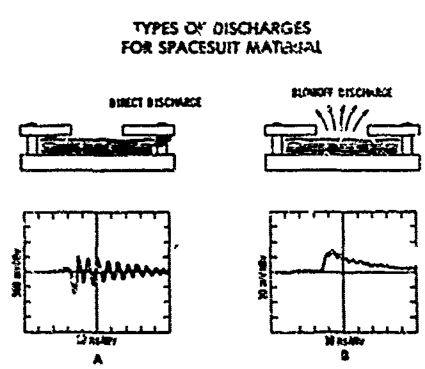


Figure 10. Types of spacesuit material arc-discharges: A. Direct. B. Blowoff.

A direct discharge from the aluminized Mylar layer was easily distinguished from a blowoff discharge by the difference in the polarity of the current pulse and the difference in the waveforms. Preliminary analysis of radio frequency (RF) radiation measurements indicate that the power radiated increases with sample size.

Tests were made at room temperature and with liquid nitrogen cooling. The glow appears brighter at 100 degrees Kelvin, compared to laboratory ambient temperature. Characteristics of the blowoff and direct discharges and the frequency of occurrence of discharge did not show a temperature dependence.

The results of these tests demonstrate the importance of a full-up chamber test. Problems about a ground return for the test sample measurements will be avoided by using the complete EVA equipment assembly. The interrelationship of fabrics, grounds, and electronic assemblies will have high fidelity. The results can be expected to be more representative of the expected in-orbit arc-discharges that will be encountered under polar-auroral charging conditions.

Space Suit Material Tests at SRI International

The arrangement shown in Figure 11 was used to investigate the behavior of a spacecraft suit element under extreme charging conditions typical of the Shuttle wake in polar orbit. A section of EMU sleeve roughly 8-inches long was placed over an insulating rod between a pair of sheet aluminum uprights (11). This simulates a suit element placed in a charging environment with no effort made to electrically bond it to adjacent components or to provide internal electrical bonding of the layers making up the sleeve element. When the electron beam was turned on, sharp twinkles of light indicating electrical discharges (analogous to the glow observed at JPL) were visually observed on various parts of the sleeve element, particularly along the stitching lines. Arc-discharges were also observed. A typical RF electromagnetic signal radiated by the discharges is shown in Figure 12. The peak electric field was 2.5 kV/m, measured approximately 15 cm from the center of the glass bell jar used for the experiment. Figure 13 shows discharges on the sleeve.

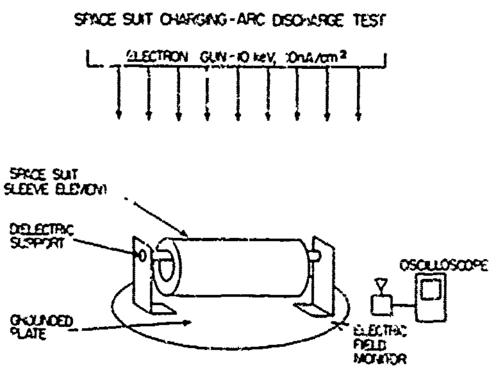


Figure 11. Experimental apparatus for EMU sleeve tests at SRI.

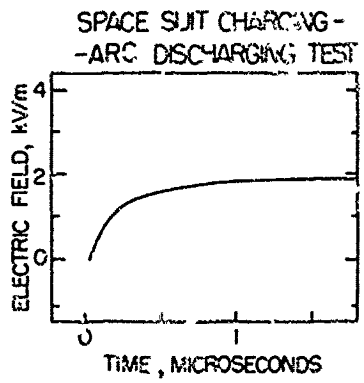


Figure 12. Radiated RF from EMU sleeve arc-discharge.

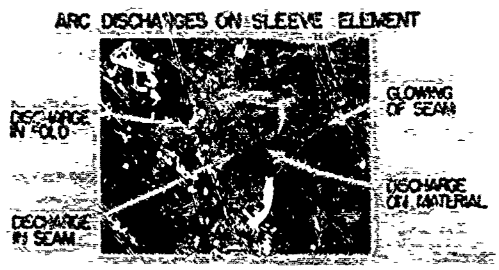


Figure 13. Arc-discharges on EMU sleeve element.

A cylindrical test sample, made from the same material and at the same time as the samples tested at JPL was also tested. Discharge currents of up to 240 A have been measured. Tests were also made with a metallic cylinder inserted in the fabric sample to simulate the surface conductivity of a perspiring astronaut. Figure 14 shows the radiated RF and Figure 15 shows the discharge current waveforms for a succession of arc-discharges. The variability of successive arc-discharge profiles, with no change in operating conditions, was notable. The fact that successive discharges under otherwise identical conditions can vary by factors of ten or more in rise time, duration, and amplitude complicates the problem of testing for their effects.

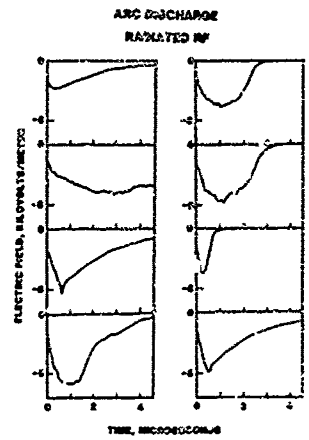


Figure 14. Radiated RF waveforms from arc-discharges on EMU fabric cylinder with internal metal liner.

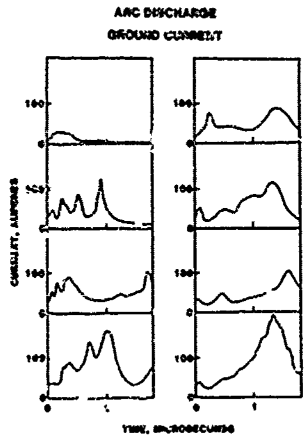


Figure 15. Discharge current waveforms from arc-discharges on EMU fabric cylinder with internal metal liner.

NASA and the EMU manufacturer report that examination of EMU components after use shows that the aluminized mylar layers break up into islands which have imperfect electrical connections. The fact that the aluminized interior layers are not electrically bonded together and to the EMU metallic sections may increase the effects of arc-discharge. Electromagnetic fields with the magnitude and rise times observed are very effective in producing EMI. Apertures and other imperfections in the shielding of spacecraft systems can result in induced interference pulses in electronic circuits.

ELECTROSTATIC DISCHAR E TESTING

Electrostatic Discharge Testing

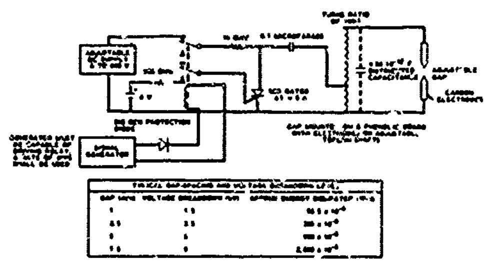
The mechanism by which arc-discharge interferes with the operations of electronics is not well understood. Alternatives include:

a. Radiated RF electromagnetic interference. The external RF can result in continuous wave signals within the equipment that can damage components or cause logic circuits to change state.

b. Injection of current pulses to external locations on the equipment. The current pulse causes surface currents from the point of injection to the "ground" or return for the pulse. The pulsed surface currents cause pulses to be induced in conductors within the equipment which, again, can damage components or change logic circuit states.

As a result, there are few widely used methods for testing the susceptibility of spacecraft systems and subsystems to the effects of charging and arc-discharge. One established method is to use the Electrostatic Discharge test method in section 6.5.2.4.1 of Military Standard (MIL-STD) 1541, Electromagnetic Compatibility Requirements for Space Systems (12). The standard calls for an arc-discharge at a distance of 30 cm as a test for radiated interference and a discharge directly to the test sample as a test for current pulse susceptibility. An arc source schematic diagram, Figure 16, is suggested in the MIL-STD, although equivalent circuitry can be used.

Opinions on the validity of the test vary widely. In practice, the test is often not performed on flight spacecraft because of apprehension that the test will cause latent damage that will later lead to spacecraft failure. Most programs that have recently developed space systems do not have full-up prototypes available for testing. The NASA/JPL Voyager program was an exception (13). Performance of the MIL-STD 1541 current injection test caused subsystem failures. The spacecraft was then reexamined and a number of changes made which eliminated the test failures. The spacecraft suffered some operational upsets during its planetary rendezvous but no subsystem failures occurred. JPL believes that the electrostatic discharge testing contributed significantly to mission success.



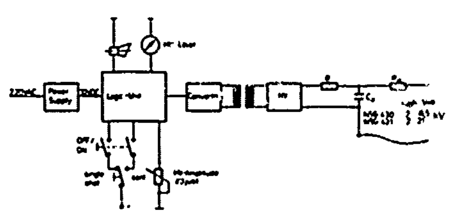


Figure 16. MIL-STD 1541 electrostatic discharge test circuit schematic.

Figure 17. Schaffner NSG-431 Electrostatic Discharge Simulator schematic.

Electrostatic Discharge Test Equipment

Implementation of the MIL-STD 1541 schematic in different ways by different organizations can result in effectively different tests. Furthermore, there is uncertainty in how dissipation of the stored energy is distributed between radiated RF and the current pulse. These factors detract from confidence in test results. Nevertheless, the MIL-STD 1541 test represents a test that has endured the scrutiny of the aerospace testing community.

An alternative test apparatus which complies with the MIL-STD 1541 allowance for equivalent type of circuity has been used for electrostatic discharge tests by one major aerospace contractor. The Schaffner Model NSG-431 Electrostatic Discharge Simulator (14) was developed to simulate discharges from static electricity accumulated by manufacturing and servicing personnel. The schematic is shown in Figure 17. The standard configuration of the simulator output circuit has a 150 picoFarad capacitor and 150 Ohm resistor to simulate human body characteristics. The variability of discharge pulses measured by SRI with no change in experimental parameters blurs the importance of selecting a different resistor-capacitor combination for bench-testing the existing EVA equipment. Other commercially available equipment can be expected to be equivalent to the Schaffner apparatus.

"Tailoring" of the MIL-STD 1541 Electrostatic Discharge test for the EVA equipment was proposed. The charging of the equipment will be modeled with charging codes to evaluate the potential to which it charges, the stored energy and likely discharge points. The MIL-STD 1541 test will then be modified to use the potential and stored energy determined by the charging codes and the current pulses injected at the likely discharge points. The usefulness of the tailored test still strongly depends on the fidelity with which the test simulates the discharge conditions in the space environment. Validation of the relationship between the laboratory tests and arc-discharges in space is necessary.

SIMULATION CHAMBER AND SPACE STUDIES OF CHARGING EFFECTS

It is important to carry out a program of testing and study which will investigate the immunity of the equipment to orbital charging effects as well as the understanding of the interaction of the spacecraft produced environment with the auroral energetic particle precipitation. A proposed two part program will ensure the absence of unexpected anomalies during polar orbital operations of manned systems (15).

SUMMARY

The evidence indicates that an astronaut carrying out EVA in the Shuttle wake in polar orbit could have his EVA equipment charge up to significant voltages if an intense aurora is encountered. Arc discharges are expected to occur, similar to those that have caused system upsets and failures in geosynchronous orbits. The possibility of hazard to the astronauts must be evaluated quickly, since polar orbit Shuttle launches will soon begin at Vandenberg AFB in California. The EVA equipment susceptibility to arc discharge generated EMI must be resolved since EVA may become necessary on any Shuttle flights, at least on a contingency basis. Furthermore, charging and arc discharge must be considered a potential hazard in the development of future generation EVA equipment.

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DISCUSSION

D.K.Davies,UK

The radiation induced charges on the EVA astronaut suit seem quite low and smaller than might be expected from contact charging, say, on the palms.
Is (or has it never been) contact charging a problem?

Author's Reply

I have no specific knowledge of contact charging. Recent successful NASA EVA servicing operations indicate there are no problems in low inclination orbits that do not encounter auroras.

E.Whipple,US

Did the charging calculations of the astronaut suit take into account the strong anisotropies in the energetic electron spectra caused by the shadowing effects of the Shuttle vehicle? There will also be anisotropies in the electron flux in the upwards versus the downward direction of atmospheric absorption. These anisotropies should lead to large differential charging between opposite sides of the astronaut suit.

Author's Reply

The calculations reported did not take into account anisotropy in the electron flux.